Original article

Gait analysis in patients undergoing ACL reconstruction according to Kenneth Jones' technique

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Abstract. The anterior cruciate ligament is essential for knee stability, and its injury, both acute and in the case of chronic knee instability, promotes meniscal degenerative alterations, as well as the onset and progression of gonarthrosis. In this retrospective study, young adults engaged in nonprofessional sportive activities undergoing ACL reconstruction by the Kenneth-Jones technique were assessed clinically and with gait analysis, to detect any deficits persisting even after rehabilitation at a follow- up of approximately 6 months. Eight patients who had undergone elective ligament reconstruction by Kenneth-Jones were assessed between the 5th and 7th month postsurgery with clinical-anamnestic investigation, including the Hughston Clinic subjective knee questionnaire and by gait analysis with the EL.I.Te. system. Gait analysis showed a reduction of ACL protection mechanisms during initial stance; furthermore, the operated limb globally exhibited greater difficulty in muscle recruitment. Residual deficits in muscle recruitment, exposing the reconstructed ligament to possible injuries, persist after a rehabilitation program and after resuming of pre-surgery activities, thus adjustment of the rehabilitative program on the basis of these findings is recommended. (www.actabiomedica.it)

Key words: Anterior cruciate ligament, Kenneth Jones, Gait analysis, EL.I.Te

Introduction

Lesions of the anterior cruciate ligament (ACL) are quite frequent, particularly in young adult male athletes, and represent the majority of the lesions of knee ligaments (1, 2). Seventy per cent of them arise in the course of sporting activities, most frequently while skiing (4).

ACL has an important role in the knee joint biomechanics in that it limits, first of all, the anterior tibial shifting and, secondly, tibial rotation and varus-valgus stress. For these reasons, ACL is of paramount importance in assuring knee stability during sport performances. Moreover, an inadequate ACL causes meniscal degenerative alterations and, as a consequence, onset and progression of gonarthrosis.

ACL lesions frequently result from low-speed traumas or traumas due to deceleration, contact with a rotational component; injury can also be caused by torsion, hyperextension, valgus stress due to contact and collision. Also acquired or constitutional anatomical alterations (5) as well as hormonal factors (in females (4, 6-8) predispose to ACL lesions.

ACL lesions clinically can occur either as an acute lesion or as an essentially chronic, recurrent knee instability. In both cases, the treatment purpose is to prevent recurrent knee instability and secondary meniscal lesions, both warning signs of early osteoarthrosis.

Treatment can be, clearly according to the indications, either reconstructive or conservative. In case of acute lesions, main indications for surgical treatment depend on instability degree and preexisting sporting

or working activity; in the case of chronic lesions, recurrent instability is the main indication.

ACL reconstruction is performed either with autologous transplant (patellar, gracilis and semitendinous tendons) or with artificial ligaments.

After a surgical or conservative treatment, rehabilitation plays a vital role in re-establishing articular range of motion, muscular strength, stability, agility and rapidity of movements, also in the simple deambulation.

Subjects having ACL lesions at different stages after surgery and rehabilitation treatment have been objects of numerous studies, mostly aimed at evaluating the knee joint function on the basis of either quadriceps strength or joint stability (9-12) but only a few aimed at evaluating bio-mechanics, kinetics and kinematics of the whole lower extremity during daily, normal activities as, for example, walking. These last studies demonstrated that a knee having an inadequate ACL during gait shows kinetic and kinematic alterations.

It is possible to demonstrate functional anomalies, though not univocal, even after ligament reconstruction followed by rehabilitation treatment (14, 18, 19). However, some months after surgery these alterations apparently progress towards normality.

The rational of the evaluation of bio-mechanics, kinetics and kinematics of the whole lower extremity is that ACL lesions, both during the phase of inability, and after its reconstruction and remodelling, can lead to neuromuscular and loads distribution adaptions in the whole limb; moreover, it is not yet clear whether a complete recovery of muscular strength and stability implies a complete recovery of articular function and not even whether all this can be influenced by some specific rehabilitation protocol.

The number of papers concerning this topic is limited and, as a consequence, there is the need to straighten out problems of great clinical importance. Therefore, we carried out a retrospective study aimed, in the course of a six-month follow-up after ACL reconstruction according to Kenneth Jones' technique, at analyzing, clinically and by means of gait analysis, young or adult non-professional athletes, in order to discover possible deficit persisting after an appropriate rehabilitation treatment.

Proprioceptive and neuromuscular co-ordination deficits persist after ACL lesions. The aim of this study was to identify the bio-mechanical parameters that indicate possible anomalies in load distribution during gait, in order to correct them by means of a selective physiotherapic protocol of muscular support.

Materials and methods

The study population consisted of patients with ACL lesions who underwent ligament reconstruction surgery with patellar tendon, according to Kenneth Jones' technique. Surgery took place at the Unit of Orthopedics, Traumatology and Functional Rehabilitation of the University of Parma, Italy, between March 23rd, 2004, and March15th, 2005.

Election surgery was performed after a 1-2 month period, preceded by preoperative rehabilitation. All patients were hospitalized.

ACL reconstruction was carried out employing a patellar tendon, according to Kenneth Jones' technique, while postoperative treatment consisted in: use of functional knee brace with articulation locked in extension for 4 weeks, then progressive passive mobilization and, for two weeks, partial loading followed by progressive increment until total load, and crutches were dismissed after the fourth week.

Postoperative course was normal and without complications in all patients. The same rehabilitation protocol was administered to all patients.

Our clinical and instrumental follow-up took place between the fifth and the seventh postoperative month on young or adult male patients that had returned to work and had had no complications, other surgery or traumas (infections, deep venous thrombosis…) which could interfere with the normal postoperative course.

We carried out two types of evaluation: the clinical-anamnestic one and the Gait Analysis, the former including filling in by each patient of the Hughston Clinic (22, 23) questionnaire.

The clinical-anamnestic analysis was carried out at the Unit of Orthopedics, Traumatology and Functional Rehabilitation of the University of Parma, while the Gait analysis was carried out at the "Don Carlo

Gnocchi" Foundation ONLUS, Center S. Maria ai Servi of Parma.

The Hughston Clinic questionnaire (22, 23) consists of 28 plain questions at which the patient has to answer using a visual analog scale (VAS).

Evaluation of muscular strength was manually performed according to the MRC (Medical Research Council) scale (24) (Table 1) while articular range was determined by means of a 180 degrees system protractor (the 180 degrees system considers as 0° the anatomic position and movements from this 0° position to any other possible direction is indicated by a positive number ranging between 0 and 180 degrees). Maximum thigh size was also measured.

Mono-podalic standing position was studied on barefooted patients.

Evaluation with Gait Analysis included kinematic parameters (speed, step duration and length, stance succession, joints angular variations) and kinetic parameters (ground interaction forces during motion). Data concerning these parameters were obtained by means of the EL.I.TE opto-electronic system (BTS, Milan, Italy) integrated by a telemetric system for recording muscular data (muscle potentials and muscle contraction intensity by means of dynamic electro-myography).

According to the S.A.F.Lo (Analysis Service of Locomotor Functionality) protocol, skin markers were applied in correspondence to C7 spine, acromion-clavicular joints, point of maximum dorsal kyphosis (approximatively T7-T8), posterior-superior iliac spines, lower sacral extremity, head of the fibula, lateral malleolus, lateral side of the fifth metatarsal heads. The recording system allows also to record at the same

time signals coming from two dynamometric platforms, the Kistler (Kistler instruments, AG, Winterthur, Switzerland) and the AMTI ones (AMTI Instrument, Massachusetts, USA), connected to a synchronized data capture computerized system.

By means of cargo cells embedded on a rigid surface, dynamometric platforms give on-going measures of mutual mechanical boosts between ground and feet.

Data coming from dynamometric platforms together with those given by kinematic analysis allowed to calculate articular moments and power.

By means of kinematics we analyzed spatial-temporal parameters of step and oscillatory behaviour of pelvis and lower limbs.

As far as articular kinetics is concerned, we measured ground reaction forces in order to evaluate joints external movements.

Locomotion analysis included recording of upright static posture and of at least ten tests of barefoot walking at normal speed. Electromyographic activity was recorded by means of surface electrodes bilaterally applied on the following muscles: rectus femoris, vastus medialis and lateralis, long head of the biceps femoris, anterior tibialis, medial gastrocnemius. On the basis of the collected data we carried out: step temporal analysis, kinematic analysis, kinetic analysis, dynamic electro-myographic analysis with basographic recording.

Significance of our results was stated by means of (1) Standard Deviation (SD) of temporal and spatial parameters concerning operated and non-operated limb, (2) Mean Value of Difference between the average kinematic and kinetic curves' peaks (MVD) of the two limbs and (3) Standard Deviation of the Difference between the average kinematic and kinetic curves' peaks (SDD) of the two limbs.

For each patient, locomotion analysis by Gait Analysis included recording of static upright posture and of at least nine tests of barefoot walking at normal speed.

Table 1. MRC (Medical Resource Council) System for muscular strength grading

Description
No muscular movement
Visible muscular movement, but no articular movement
Articular movement is present, but no counter-gravity
Countergravity movement is present, but no counter-resistance
Counter-resistance movement is present, but strength is weaker than normal
Normal strength

Case study and results

The study was carried out on 8 patients, males, of young-adult age. Clinical-anamnestic data of these

patients were analyzed and the Hughston Clinic questionnaire was filled in (Table 2). Follow up of patients after surgery averaged around 6,5 months.

Table 2. Results of clinical-anamnestic assessment of 8 patients after ACL reconstruction by Kenneth-Jones technique at approximately 6-month follow-up

Parameter		
Age range: Min = 21 years Max= 33 years mean: 28.3 years		
	No. patients	%
Physical activity		
Non-professional	8	100
Modality of injury		
During sports activity	8	100
Tendon rupture on the right side		
Right	4	50
Left	4	50
History of knee injury?		
no	8	100
Hughston Clinic questionnaire		
Lowest		21
Highest		97
Mean		70
Sensory disorders		
no	8	100
other		
Internal tension sensation during maximum flexion	2	25

All the patients had returned to a normal working and mild sport activity.

Temporal parameters (Table 3) show that walking speed of ACL lesioned patients overlaps that of normal subjects in terms of time but with a non significant (5%; DS=0,16) decrease in step length of the operated limb.

Stance phase duration results prolonged in both limbs but slightly reduced in the operated one. The DS of operated limb (38,1) and DS of normal limb (19,2) results significantly different from normalized stance duration of normal subjects.

Spatial parameters show a marked asymmetry in the length of the anterior step that results longer in the operated limb. The hindfoot is static: operated patients use more the anterior step. Step results wider, and this guarantees a wider base of support on the frontal plane.

As far as knee kinematics are concerned, on the operated limb, at the terminal stance (Figure 1), there is a reduction of flexion, with Mean Value of Difference of 9 degrees between flexion kinematic curves peaks, with a significant Standard Deviation of the Difference (SDD=11,8%) between the kinematic curve peaks of both limbs. In fact, in the first part of the stance phase, the operated knee flexes more due to the lesser control from the quadriceps muscle, particularly during the second shock absorption of the

Table 3. Mean values of spatial-temporal parameters

	Operated side	DS	Unoperated side	DS
Temporal parameters				
Duration of stance [msec]	1000	107.0	1060	53.1
Duration of swing [msec]	490	53.8	450	34.7
Duration of stance [% step]	67	2.4	70	1.3
Duration of swing [% step]	33	2.3	30	1.2
Duration of step [msec]	1490	38.1	1510	27.1
Cadence [steps/min]		80		
Duration of double stance [msec]	200	38.1	240	19.2
Duration of double stance [% step]	14	2.8	17	1.6
Spatial parameters				
Length of anterior step [mm]	598.34	81.2	515.53	66.7
Speed [m/sec]	0.71	0.16	0.70	0.07
Speed of swing [m/sec]	1.99	0.4	2.36	0.5
Step length [mm]	1014.65	161.8	1065.57	119.1
Step width [mm]		167.79		
Mean speed [m/sec]		0.71		
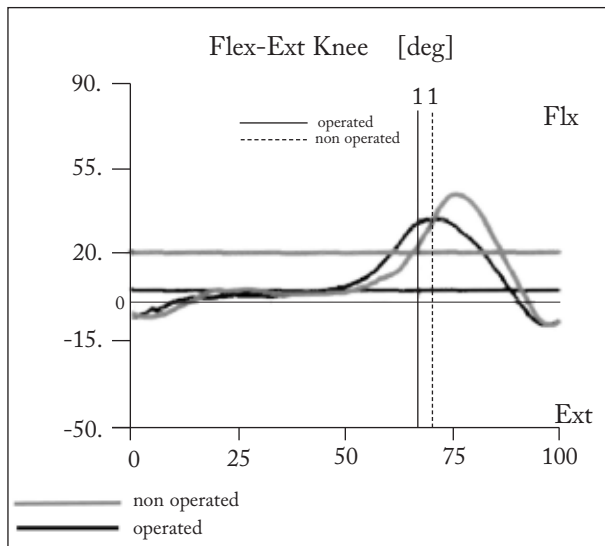
Figure 1. Knee kinematics: difference between peaks of flexion curves

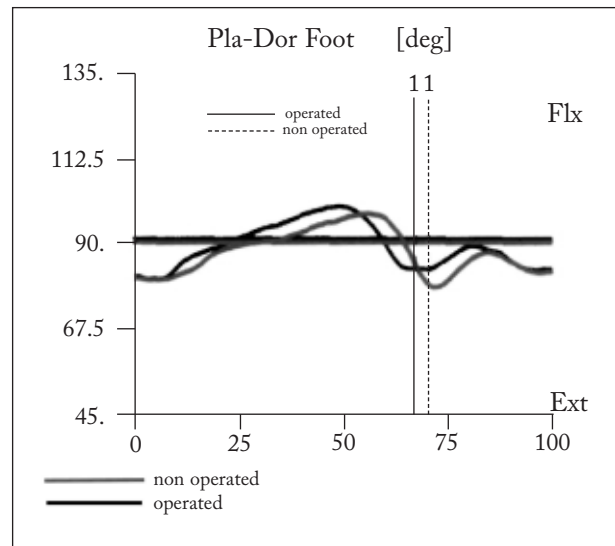**Figure 2**. Tibio-tarsal joint kinematics: reduction of plantar flexion in the operated limb

ground contact force. Total limb excursion results reduced by two thirds. As far as kinematics of the tibio-tarsal joint are concerned, in the operated limb the range of plantar dorsiflexion results reduced. In fact, there is an increased plantar flexion during loading response and, as a consequence, a reduction of the heel rolling effect so that tibia advancement is not too quick. In particular, plantar flexion reduces in the terminal stance (Figure 2). In any instance, in the operated limb the hindfoot axis is more horizontal than in the normal limb (Figure 3).

Always pelvis is downward inclined on the operated limb (Figure 4) and predominantly rotated towards it during the swing of the lower limb.
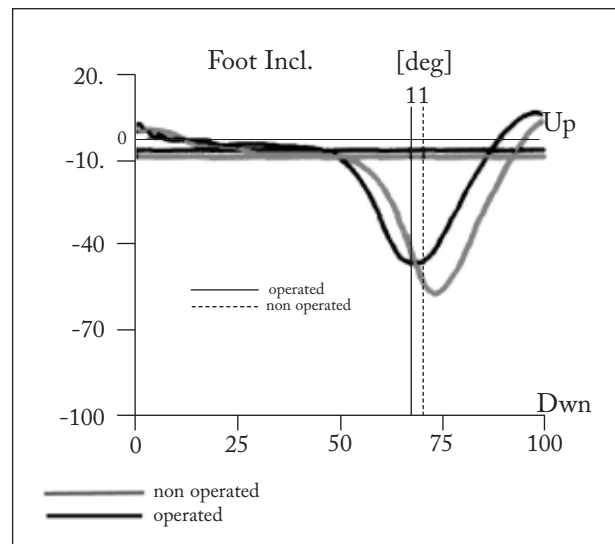
In the operated limb, at the moment of contact, the leg is downward and forward inclined and extrarotated. Thus, the contact with the ground takes place on the plant of the foot.

Finally, excursion of distal segments of the operated limb results reduced.

As far as knee kinetics are concerned, in the terminal stance of the operated limb, flexion moment results reduced, with a significant Standard Deviation of the Difference (SDD=14,1%), between the kinetic curves peaks of both limbs, while extension moment results increased (32,2 Newton/m/kg versus 21,0 Newton/m/kg) (Figure 5). Varus moment results in-

Figure 3. Foot kinematics: more horizontal hindfoot axis in the operated limb than in the non-operated limb

creased in the operated limb (24,6 Newton/m/kg versus 18,4 Newton/m/kg) (Figure 6).

Maximal "power generation" of the operated knee results reduced (39,9 W/kg versus 59,6 W/kg) with a significant Mean Value of the Difference (19,7 W/kg) between the kinetic curves peaks of the limbs (Figure 7).
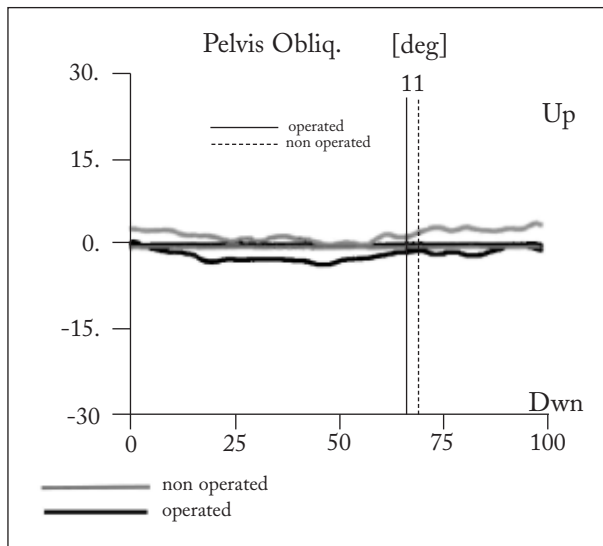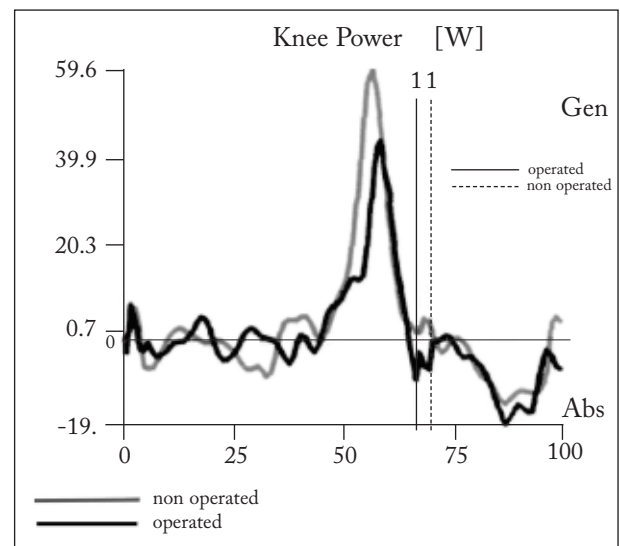
Figure 4. Pelvis kinematics: rotation of the pelvis during anterior step
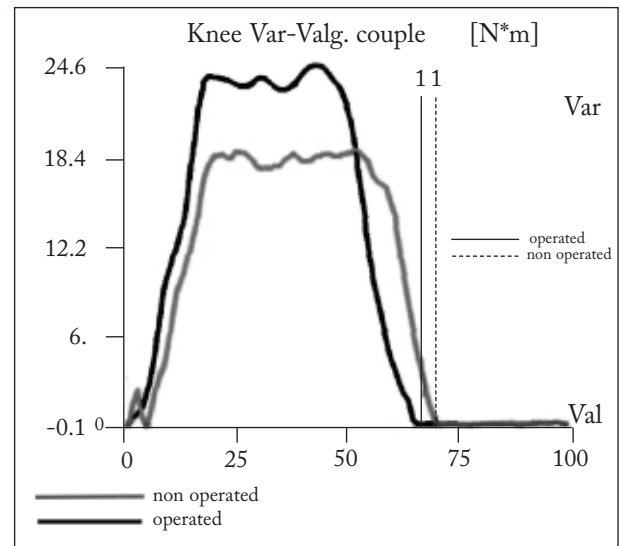
Figure 6. Knee cinetics: increased varus moment in the operated limb
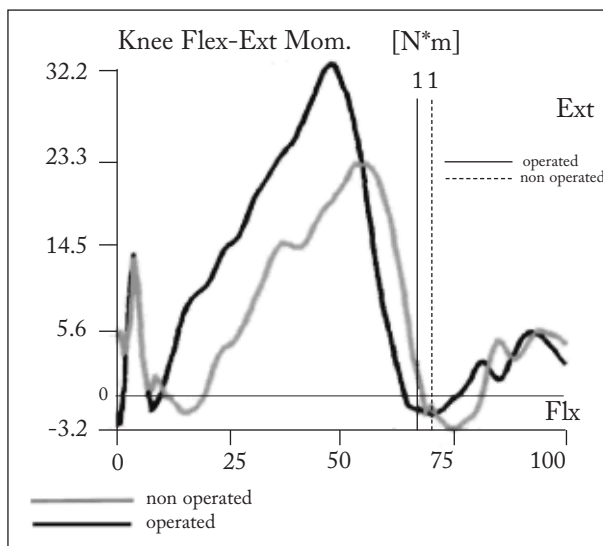
Figure 5. Knee cinetics: reduction of flexion moment and increase of extension moment of the operated limb

Figure 7. Knee cinetics: difference between peaks of cinetics curves (lower peak of the operated limb)

Dynamic electro-myography with basographic recording showed that:

1) especially in the operated limb, in the terminal stance the activity of the rectus femoris muscle results reduced;

2) especially in the operated limb, there is a lower but continuous, irregular tonic activity of vasti muscles. This activity is yet present at the terminal stance

and lasts up to the swing phase and to that of weight acceptance. Vasti's concentric activity is reduced (Figure 8), appearing not completely directed to knee extension in the terminal swing and to knee efficient stiffness. In physiological conditions the intensity of vasti's contraction is of critical importance for ensuring safe limb stability;

3) on the operated limb, hamstring contraction

was prolonged with enhanced activation at the beginning of loading, in order to protect knee from hyperextension (Figure 9);

4) on the non-operated limb, activity of the anterior tibialis muscle is lower, with non physiological peaks during mid and terminal stance. On the operated limb, a late activity of this muscle is seen both in final load and during the swing phase (Fig. 10). In this way, slowing down of tibiotarsal (joint) movement produces partial absorption of the impact that comes from rapid limb load;

5) on the non-operated limb, a larger activation of gastrocnemius not only in the push-off phase but also in an earlier phase is present (Figure 11). More-

over, on the operated limb, a reduced, irregular tonic activity is seen during the second stance phase. This is expression of a reduced concentric activity, not useful for efficient plantar push-off;

6) in the second part of load phase, the lower activity of medial vastus and gastrocnemius and the increased activity of the hamstring muscles probably compensate the tibial anteposition.

Discussion

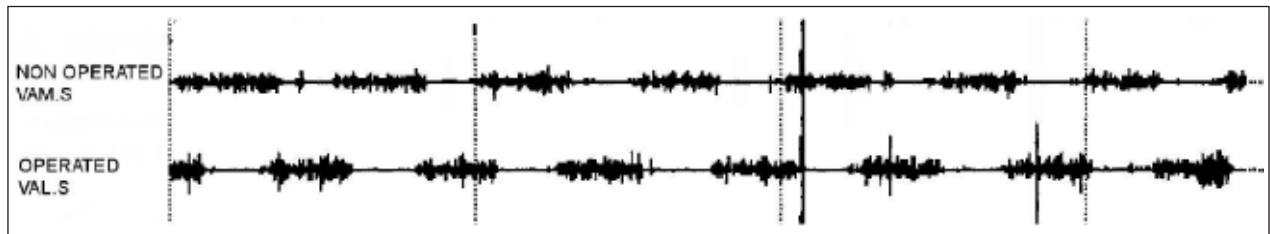The main functional alterations observed in the operated limb can be summarized as follows:

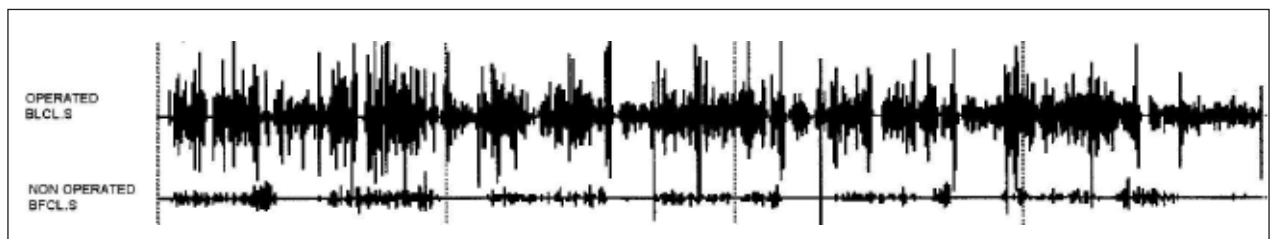**Figure 8**. Dynamic electro-myography: reduction of vasti's concentric activity in the operated limb

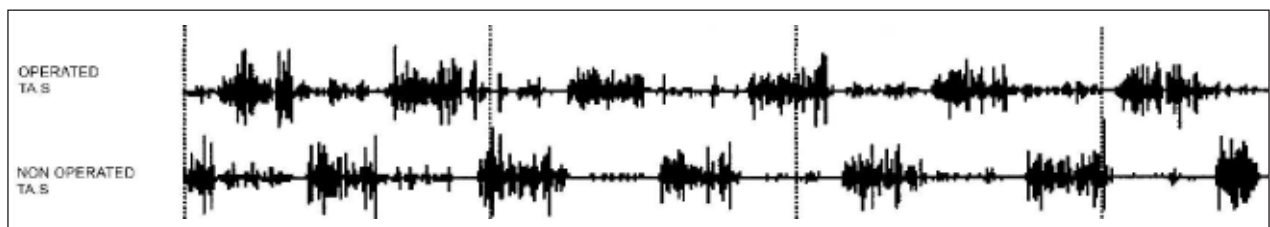**Figure 9**. Dynamic electro-myography: prolonged hamstring contraction

Figure 10. Dynamic electro-myography: anterior tibial muscle late activity in the operated limb
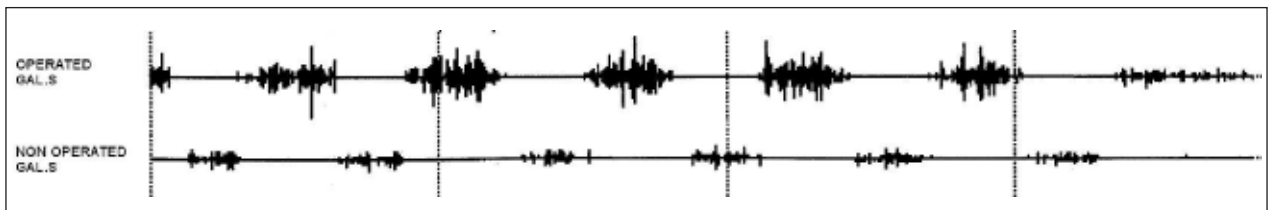
Figure 11. Dynamic electro-myography: reduced, irregular tonic activity of gastrocnemius in the operated limb

1) due to the constant activity, particularly during stance, of the anterior tibialis muscle, the center of pressure progression decreases and, as a consequence, also ankle dorsiflexion moment decreases;

2) during stance, the deficit in plantar flexor recruitment causes a protracted dorsiflexion but also a longer delay in heel clearance. Thus, propulsive strength results decreased and delayed;

3) the distal propelling deficit imposes a compensation strategy in order to obtain the swing set by the specific action of rectus femoris as a drive of forward thigh shifting;

4) quadriceps intervention on vasti and rectus femoris behalf is necessary to oppose knee flexion moment. In addition to flexion control, the quadriceps muscle produces a anterior shear stress which is opposed by anterior cruciate ligament. Such an "anterior drawer" is limited by the antagonist activity of hamstring muscles which are precociously recruited, at about middle swing. Lack of contraction at the same time of quadriceps and of the knee extensors, together with the good knee extension, is expression of the low tension, despite their precocious recruitment, of hamstring muscles. For these reasons, 6 months after surgery, during the stance phase, optimal protection of the anterior cruciate ligament results to be decreased;

5) it's important to emphasize knee valgus thrust during the initial stance due, while being the knee in extension, to the medial thigh inclination and lateral leg inclination;

6) on frontal plane, trunks shifting toward the non operated limb nullifies hip adductor moment but leaves the pelvis horizontal;

7) Trendelenburg's sign is negative but a deficit of abductor muscles may be detected.

Conclusions

In functional terms, the solutions that the locomotional strategy adopts in the operated limb appear to be aimed at protecting the knee, by reducing to a minimum external stress on the frontal plane.

In the hip, the larger contralateral pelvis fall is caused by the weak contraction of abductor muscles (gluteus medius, gluteus minimus, upper fascia of the gluteus maximus and tensor fascia lata). During the phase of loading response, pelvis antiversion is due to the weakness of quadriceps muscle, since this is a phase of high request. In fact, in this phase heel rotation implies knee flexion, which involves direct control from quadriceps.

The "voluntary" decrease of quadriceps action, aimed at protecting the anterior cruciate ligament, is a sophisticated mechanism of compensation, in that it shifts the ground reaction force before the knee. The tibia actively shifts backward.

On the operated limb, propelling deficit and abductors recruitment deficit appear more marked, with higher pelvis fall speed. Shock absorption of the load-bearing limb by muscular action is smaller and, consequently, 6 months after surgery hip and knee total load results increased.

The reduced knee flexion during initial loading is barely sufficient to damp the load impact on the limb but increases the stability necessary to make safe the load. This control is obtained by vasti muscles, with a minor participation of rectus femoris muscle, since its flexion activity would increase hip passive flexion moment.

The inadequate knee flexion reduces intensity of the impact on the ground. The load impact directly transfers load from femur to tibia, without any muscular damping. However, the operated limb is protected

from hyperextension by a muscular equilibrium with protracted activation of hamstring muscles in the initial stance phase.

In general, in the operated limb it is more difficult to recruit muscles but there are no unwanted pathological co-contractions.

As far as motor rehabilitation is concerned, biomechanics of exercise varies according to some variables: way to practice exercises (open or closed kinetic chain), excursion and joint angle and trunk position (25).

Instrumental data from gait analysis demonstrate that flexor muscles strengthening exercises in open chain with the progressive increase of active flexion (26) produce a progressive increase in ACL tension. This increase is due to contraction of flexor muscles that produce an anteroposterior force on the tibial plate (26).

These kinetic open chain exercises are at risk since produce an excessive stress on the neo-ligament. An excessive stress is also produced by open chain exercises consisting in active extension from maximal flexion up to 60°. On the contrary, between 60° of flexion and complete extension there is a "safe" range of motion. Thus isotonic exercises with flexion ranging between 60° and 0° do not cause any damage to the neo-ligament (27).

Closed kinetic chain exercises are less risky, however it should be emphasized that, also in their course, the stress on ACL increases as knee flexion increases. Moreover, they are influenced by trunk position that, if bent too far forward, causes a postural contraction of flexor muscles and the negative effects described by Wilk and al. (28).

On the basis of what above reported, we have to stress that, after ACL reconstruction with patellar tendon, it is necessary an intense functional rehabilitation aimed at:

a) increasing knee articular range in the operated limb;

b) stimulating articular movement, particularly of the hip and the knee of the operated limb in extension, with stretching exercises, in order to induce postural re-alignment;

c) modulating hip and knee under load semi-flexion attitude, especially with pelvis placement exercises, for active extension of hips by means of pelvis uplifting on operated limb.

As far as muscles are concerned, it's clearly necessary to obtain an improvement of muscular tone of the rectus femoris muscle of both sides, but particularly of the operated side; of the hamstring muscle of both sides, but particularly of the operated side and of the vasti of both sides.

It's likewise necessary to obtain an improvement of muscular strength of the quadriceps muscles of both sides; of the hamstrings muscles of the operated side and of the surals muscles of the operated side.

Deambulation rehabilitation provides to increase step length by increasing, on the operated side, hip and knee flexion in the final swing phase as well as by stimulating the patient to touch the ground with the point of the foot; to better the use of the hindfoot and to balance length of anterior step and duration of whole rhythmic step for a more physiological alternation of stance and swing.

Finally, proprioceptive re-education aims at a postural and gesture control by means of a maximal improvement of the proprioceptive afferents of the joint and muscle receptors. This should give better sensory information about body status, relations between the segments and their position in the space (29). Proprioceptive rehabilitation should be carried out in order to increment and to make symmetric pelvis rotation through rehabilitation of lumbopelvic rhythm.

Proprioceptive rehabilitation is necessary also for a correct load distribution on a frontal plane and for the control of antigravity musculature stiffness and for teaching a correct length of posterior step. On the long run, a complete rehabilitation after an ACL ligament reconstruction is achieved in 75-95% of subjects and is not successful in 8% of patiens (recurring instability, transplant inadequacy, arthrofibrosis).

After ACL reconstruction, for a correct rehabilitation gait analysis data are needed. They allow to know the biomechanics of peri-articular muscles, of knee flexors in particular, that shift tibia backward, especially in the phase of maximal flexion. Exercises in closed kinetic chain with lower flextion angle and leaning trunk are necessary, also many months after surgery, for protection of the neo-ligament.

Anterior cruciate ligament reconstruction is aimed at returning functional levels to normality and at preventing secondary damages.

This study emphasizes the importance of a gait analysis in order to reveal deficits persisting after the rehabilitative treatment and then to take measures for protecting integrity of the neo-ligament.

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